REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
23-04-2012	Final Technical	6/1/09-12/1/11

4. TITLE AND SUBTITLE
BIO-INSPIRED SCHEMES FOR GLOBAL OPTIMIZATION AND ONLINE DISTRIBUTED SEARCH

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-09-1-0368

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Alfredo Garcia
Department of Systems & Information Engineering

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Virginia
Charlottesville, VA 2294

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 N Randolph St
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
afrl-osr-va-tr-2012-1005
FA9550-09-1-0368

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A recent strand of research in optimization methods has been inspired by collective forms of intelligence present in many biological systems (e.g. swarming, flocking). In these systems, a great deal of coordination is achieved under relatively minimal communication requirements. In this research project we have developed new methods for global optimization and distributed search that are inspired by certain biological systems.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Fariba Fahroo
UU	UU	UU	SAR	4	19b. TELEPHONE NUMBER *(Include area code)* DSN 426-8429

BIO-INSPIRED SCHEMES for GLOBAL OPTIMIZATION and ONLINE DISTRIBUTED SEARCH

FA9550-09-1-0368

Final Report

PI: Alfredo Garcia,
Department of Systems & Information Engineering
University of Virginia
Charlottesville, VA 2294

1. Objectives

A recent strand of research in optimization methods has been inspired by collective forms of intelligence present in many biological systems (e.g. swarming, flocking). In these systems, a great deal of coordination is achieved under relatively minimal communication requirements. In this research project we have developed new methods for global optimization and distributed search that are inspired by certain biological systems.

2. Results

2.a In [1] and [2], we developed a distributed algorithm based upon the notion of *stigmergy*. By disseminating a scent, searching agents could avoid inefficient duplication of search efforts. This scheme was shown to work well in scenarios in which searching agents are homogeneous (i.e. they are equipped with the same sensor technology).

2.b In [3] we have considered improvements to the cross-entropy (CE) method which are also inspired by stigmergy (see 2.a). In the CE method, a sampling distribution within a given class is selected at each iteration. The selected sampling distribution minimizes the Kullback-Leibler divergence with respect to a reference distribution. This reference distribution is meant to reflect the quality of solutions found so far and is updated after every iteration. For the CE method, convergence to global optima almost surely (or with probability 1) can be established under certain conditions. A Markov chain model (where the state space is an index set of the class of sampling distributions) can be used to analyze the CE method. We have shown that the speed of convergence (dictated by the second largest eigenvalue) is directly related to the "worst" possible state. In other words, there is a state (i.e., a sampling distribution) in which the process remains for a relatively large number of iterations. Using a *repulsive* potential for several interacting processes, we have shown that the magnitude of the second largest eigenvalue can be effectively reduced thus speeding up convergence to global optima.

2.c In [5], we present a novel approach in which parallel annealing processes interact in a manner that expedites the identification of a globally optimal solution. A first annealing process operates at a faster time scale and has a drift function that converges to a non-zero (but relatively small) noise level. A second annealing (operating a slower time scale) is subject to a modified drift term in which the steepest descent direction is perturbed with the first process's density gradient. This additional term ensures that the second annealing process is "repelled" by the proximity of the first process. As a result, the first annealing process (which quickly identifies locally optimal solutions) allows the second annealing process to bypass locally optimal solutions recently identified so that its own "cooling schedule" can be made to converge to zero at a faster

rate. We show that when compared to independent annealing processes, the proposed scheme can increase the speed of convergence and/or the quality of solutions identified in finite time at the expense of minimal additional computational overhead.

2.d The notion of interacting annealing processes motivated a new application in the context of congestion games. In [4], we develop a pricing scheme for controlling annealing process that interact through a congestion externality.

3. Accomplishments/New Findings

The papers summarized above deliver on the research tasks originally proposed in this project.

4. Personnel Supported

Alfredo Garcia	PI
Yuting Wang	PhD student
Yue Sun	PhD student

5. Publications:

See references below.

6. Interactions/Transitions

a. "Distributed Learning and Optimization" invited talk, Department of Industrial Engineering and Management Science, Northwestern University, November 2010

b. "Controlling Congestion Games", First Annual INFORMS Transportation Science and Logistics Society Workshop, Asilomar CA, June 2011

c. "Bioinspired Methods for Optimization and Control", invited talk, School of Electronic, Information and Electrical Engineering, Jiao Tong University, (Shanghai, China) June 2012

7. New discoveries, inventions, or patent disclosures.
None

References

[1] "A Bio-Inspired Scheme for Coordinated Online Search" A. Garcia, F. Pedraza and Ch. Li, *IEEE Transactions on Automatic Control*, Vol. 55 No. 9 (2010) pp. 2142-2148

[2] "Rational Swarms for Global Optimization" Ch. Li and A. Garcia, *International Journal of System Control and Information Processing*, (2011) accepted for publication

[3] "Speeding Up Cross Entropy Method for Global Optimization" (2012) Y. Wang and A. Garcia, *European Journal of Opeational Research*, submitted.

[4] "Cap and Trade for Congestion Control" (2012) A. Garcia and M. Hong, *Dynamic Games and Applications*, revised and resubmitted.

[5] "Interactive Annealing for Global Optimization" (2012) Y. Sun and A. Garcia, *Journal of Optimization Theory and Applications*, submitted.